THE GRACE MISSION:
THE CHALLENGES OF USING MICRON-LEVEL SATELLITE-TO-SATELLITE RANGING TO MEASURE THE EARTH'S GRAVITY FIELD

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ABSTRACT – The GRACE Mission, to be launched in mid-2001, will provide an unprecedented map of the Earth's gravity field every month. This is accomplished through the use of precise K-band carrier phase tracking between the two GRACE spacecraft. In this paper, we outline the challenges associated with this micron-level satellite-to-satellite ranging, the solutions used by the GRACE project, and the expected science applications of the data.

1 - INTRODUCTION

The need for a mission to obtain an accurate set of global, homogeneous, high-resolution gravity measurements has been articulated consistently since the Williamstown Conference in 1969. The requirements for such a mission are stated in numerous reports of the National Research Council (1997) and a number of international scientific programs, including the World Ocean Circulation Experiment, the Climate Variability Program and the Global Ocean Observing System. The factors recognized in these reports have led NASA and the Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR), to select the GRACE Mission for flight under the Earth System Science Pathfinder (ESSP) program.

The GRACE Mission is a microwave satellite-to-satellite tracking mission (SST) with an inclination of 89 degrees and an initial altitude of 450 – 500 km that (a) delivers a static gravity field that meets the major requirements for the uses of satellite altimeter data by the oceanographic community, and (b) measures the time-varying gravity signatures associated with mass redistribution among the earth's atmosphere, ocean, and solid components. These latter variations are important indicators of the processes of mass, momentum, and energy exchange among the earth's components. The mission's long lifetime (5 years) and low altitude orbit provide a unique opportunity to simultaneously increase the spatial resolution of gravity field models, while decreasing errors due inadequate sampling of temporal variations. While ensuring high accuracy estimates of the static field, the long mission lifetime also yields accurate estimates of the time variations in the geoid, themselves leading to exciting and unique science goals.

We have performed extensive estimates of the expected GRACE geoid errors based on both a simplified error-propagation approach and full supercomputer simulations. Error sources considered included multipath, antenna, RF "front end", time-tags, digital signal processing, frequency standard (oscillator), system noise (SNR), ionosphere, neutral atmosphere, accelerometer, orbit, attitude control, and center of gravity offset. Results from the two approaches agree to a level that is consistent with estimated performance margins. The full supercomputer simulations extended to degree 100, while the error propagation approach, because of its simplicity, could be extended to degree 200. Figure 1 provides a summary of the expected geoid errors from the GRACE Mission, and some example geophysical effects to be measured.

Based on these studies, the data from GRACE should enable:

• reduction of the uncertainty in the poleward heat flux in the ocean at least 30 percent,
• long-term studies of sea level, upper-ocean heat content, and surface currents by improving both geoid and reprocessed orbit accuracy for GEOSAT, ERS-1, and ERS-2,
• determination of the global distribution of absolute surface geostrophic ocean current in concert with altimetry.

Importantly and uniquely, GRACE will not merely take a snapshot of the geoid, but will monitor the geoid variations for a 5 year period. By producing a new geoid every month, GRACE will help unravel the complex processes affecting our climate:

• providing unprecedented measurement of large scale evapo-transpiration, soil moisture, and the hydrologic cycle,
• monitor the changes in deep ocean currents at the level of 1 mm/sec,
• measuring the depletion of large aquifers (to an accuracy of a few percent of the estimated depletion rate for large aquifers such as the Ogallalla),
• monitoring sea level rise and allowing ocean thermal expansion to be separated from increase in mass,
• measuring changes in the mass distribution of polar ice.
• GRACE's accurate geoid models will enable new understanding of lower-mantle viscosity and the forces and trajectories of subducted slabs in the mantle.

The fundamental algorithms to improve the mathematical model of the Earth's gravity field exist in literature and have been used by UTCSR and JPL in simulations to assess the accuracy of the GRACE mission. Algorithms to process the microwave range, range-rate, and range acceleration data, as well as the GPS data, for the satellites exist at JPL and have been tested on existing low-Earth orbiters and in simulation. Mission-specific data processing algorithms and models will be developed in parallel with the development of the satellite and instrumentation. After validation, SST and GPS data from GRACE will be placed in the EOS DIS in a timely mannerfor analysis by the international community.

We plan to produce three major classes of data products (GRACE Team, 1999):

1) Validated satellite-to-satellite data: biased range (carrier phase), range rate (doppler), and range acceleration data, time tagged and geolocated. The GPS tracking data from the GRACE satellites will also be included for those interested in performing their own precise orbit determination solutions.
2) Precise ephemerides for the GRACE satellites, determined from the GPS tracking, and a form partial derivatives at each trajectory point of each of the above data types (range, range-rate, range acceleration) with respect to a description of the gravity field (which may not be spherical harmonics for file size reasons). The combination of the precise trajectory and the satellite-to-satellite acceleration data also allow straightforward local solutions (as opposed to global spherical harmonic models) for gravity anomalies due to trenches, mountain ranges, and other small spatial scale features.
3) High level solutions for targeted geophysical quantities of interest, including sea level rise, various parameterizations of polar ice sheet changes, and hydrologic histories for selected areas, such as the Mississippi Basin.

Geoid Signals and Accuracies expected from GRACE

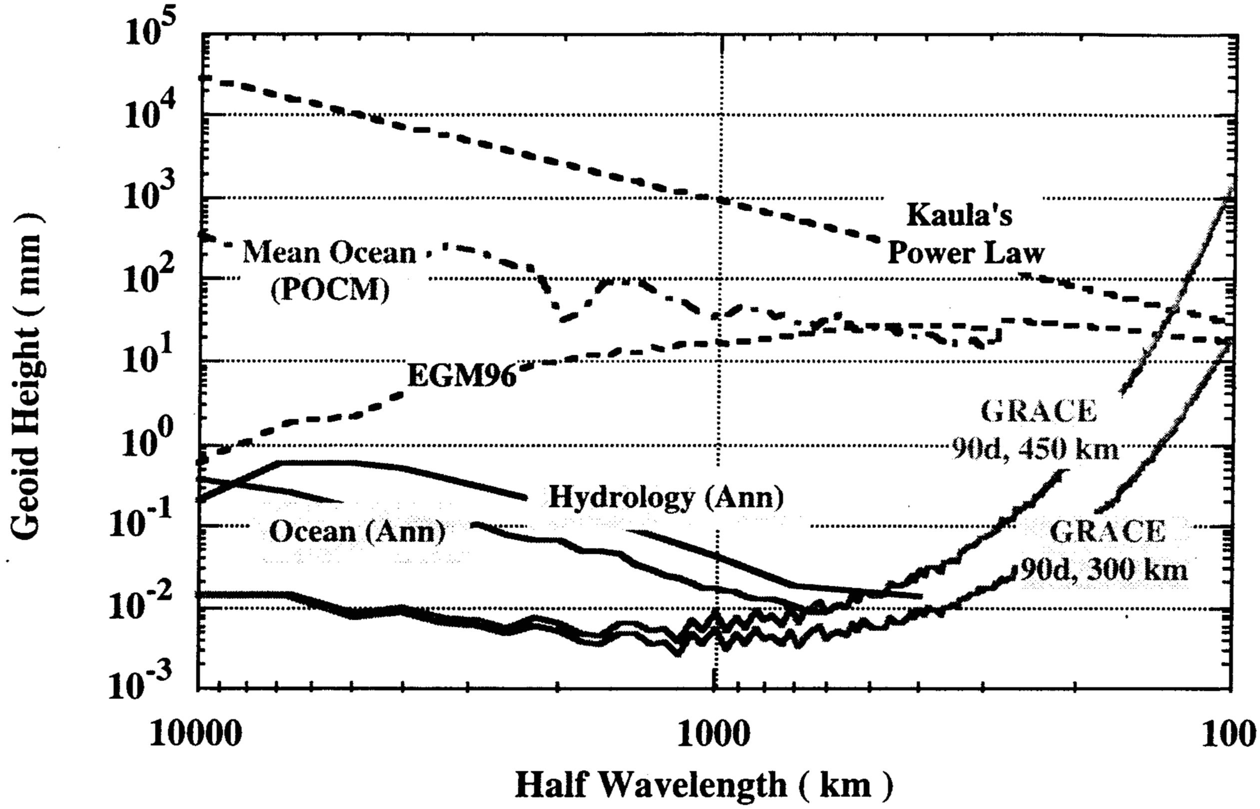

Figure 1. Expected geoid errors from GRACE based on 90 days of data, and some geophysical effects.

These models of the gravity field will be distributed to the ocean science community through the PODAAC at JPL, and a companion data system at GFZ, within 30 to 90 days of data acquisition.

In order to meet the challenging GRACE science goals, a significant amount of engineering and analysis was devoted to removing the multitude of effects which can become major issues at the micron-levels of accuracy GRACE intends to realize. We discuss some of them in more detail below.

2- Drag and Other Surface Force Effects

The GRACE accelerometer is derived from the ASTRE and STAR accelerometers that have been developed by the Office National d'Études et de Recherches Aérospatiales (ONERA) for the European Space Agency (ESA) and for the French Space Agency CNES. The principal is to provide a proof mass isolated from surface force effects, providing in effect a gravitational "test particle" in free fall. This is accomplished by electrostatically suspending and controlling the position of a proof mass between capacitor plates that are fixed to the spacecraft. To keep the proof mass centered, the voltages suspending it must be adjusted using a control loop. Thus, the suspension control voltage is a measure of the nongravitational forces on the spacecraft. The STAR accelerometer, which is the French contribution to the German CHAMP mission, has a planned resolution of 10^{-9} ms^{-2} integrated over the frequency bandwidth of 2×10^{-4} Hz to 0.1 Hz. Its full-scale range is 10^{-3} ms^{-2}. The expected resolution is based on accepted error analysis, and the sensor head geometry is based on results from the ASTRE model. Because of the GRACE orbit and the low-vibration design of the spacecraft, the full-scale range has been reduced to 5×10^{-5} ms^{-2}. This, combined with 0.1-K thermal control, allows the sensor core capacitive gaps to be increased from 75 μm to 175 μm and the proof mass offset voltage to be reduced from 20 V to 10 V. This results in a smaller acceleration bias by a factor of 20, and more importantly, bias fluctuations are also reduced by a factor of 20. The combined effect of these changes is a resolution on the order of 10^{-10} ms^{-2}. The essentially constant bias and scale factors must be estimated on orbit, and we have performed extensive simulations to verify the estimability and separability of these factors from the gravity field. Table 1 provides a summary of the results of such experiments.

Scale Factor Estimation Error

	Radial	*Transverse*	*Normal*
Initial Value	*0.9814*	*1.0266*	*1.0145*
Estimation Error	*0.0038 (0.39 %)*	*<0.00001 (<0.001 %)*	*0.0008 (0.08 %)*

Bias Estimation Error ($\times 10^{-6}$)

	Radial	*Transverse*	*Normal*
Initial Value	*-0.987*	*1.259*	*-1.492*
Estimation Error	*-0.001 (0.94 %)*	*0.0001 (0.01 %)*	*-0.001 (0.07 %)*

Table 1. Summary of accelerometer scale factor and bias estimation in presence of full gravity field solution. Note that the results meet the requirements of 0.01% in the transverse ("along track") direction for scale factor and 10^{-10} ms^{-2} for the bias.

3- Center of Mass Control and Other Calibrations

Several precise calibrations are required for GRACE. The first is to co-locate the center of mass of the spacecraft and the accelerometer proof mass to within about 100 microns. If the distance is larger, the requirements on the attitude control and knowledge become too stringent to remove the atttitude effects from the accelerometer measurements. The measurement of the center of mass offset is performed on orbit with the following maneuver:

1) Actuate magnetic torquers for y and z axes (separately) to rotate the spacecraft at 0.1 Hz for 60 s.
2) Read out implied centripedal acceleration from accelerometer and solve for implied cg offset using $a = \alpha \times d + \omega \times (\omega \times d)$ where d = cg offset

Detailed simulations with realisitic error models indicate that this measurement can be made to roughly 30 micron accuracy in each axis. Following the measurement, the center of mass is adjusted with a trim system composed of six motor-driven masses—a redundant pair in each of the three axes of the satellites. The trim system has a resolution of 20 μm.

The second calibration is the alignment of the K-band boresight with the star camera axes using a nodding maneuver and correlation between satellite attitude and range measurements on the microwave link. The basic idea is to measure the range variations while varying the spacecraft attitude and observing that this change in range involves the following relationship

$$\Delta R = DA(\theta_{var} + \Delta\theta_{POD} + \Delta\text{offset}) + \Delta R_{grav} + \Delta R_{nongrav}$$

where ΔR is the range change, D is a direction cosine transformation, A the amplitude of the attitude variation, θ_{var} is the attitude variation, $\Delta\theta_{POD}$ the change in attitude due to relative orbital motion of the two GRACE spacecraft, Δoffset is the angular alignment between the K-band boresight and the star camera (the angle to be solved for), and the last two terms are the changes in range to the gravitational and nongravitational effects on the spacecraft. Careful analysis of this calibration maneuver indicates that the offset angle can be can be measured with an accuracy of better than 0.3 mrad.

Knowledge of the alignment of star camera axes to accelerometer axes is important for projecting the measurements on the nongravitational forces into the inertial reference frame. This must be done to within 0.3 mrad, with a goal of 0.1 mrad. This is accomplished by integrating the star cameras and accelerometers onto a single low-CTE fixture. This is the only critical alignment that cannot be refined on orbit.

4- Spacecraft Stability

Because in the GRACE mission the satellites themselves act as the "proof masses" through which the gravitational field is sensed, the satellite design is crucial to the distance between the centers of mass of the two satellites. Thus, the location of the centers of mass must be determinable relative to the instruments on the satellite. In addition, the accelerometer proof mass must be close to the center of mass to avoid confusing internal satellite forces with external, nongravitational forces. Because of these considerations, the satellite must be carefully designed for mass stability, dimensional stability, and aerodynamic configuration.

To minimize the consumption of cold gas for attitude control, the center of mass needs to be collocated (to an accuracy of 5 mm) with the center of action of the aerodynamic forces. But to minimize disturbances of the accelerometer, the center of mass also needs to be collocated (to an accuracy of 100 μm) with the center of mass of the proof mass of the accelerometer. This will be accomplished by first placing the equipment within the defined aerodynamic shape, then adding balance weights to get within 500 μm, and once in orbit, using a center-of-mass trim system to bring the collocation to within approximately 20 μm. As shown in Figure 2, two tanks of pressurized nitrogen are symmetrically located about the center of mass of each satellite. The tanks are connected together so that internal pressure can be balanced. The line connecting the tanks has a solenoid valve that allows the tanks to be isolated from each other during science operations. Otherwise, even small temperature variations between the tanks would produce motions in the satellite center of mass that could mimic gravity effects. This valve will be opened periodically (~ 6 months) to equalize pressure between the tanks, thereby avoiding significant long term drifts in the center of mass.

With the exception of the small solenoid thruster valves, there are no moving parts on the satellite in the science mode. The body-fixed solar panels are rigid and insulated on the back side to prevent thermal warping.

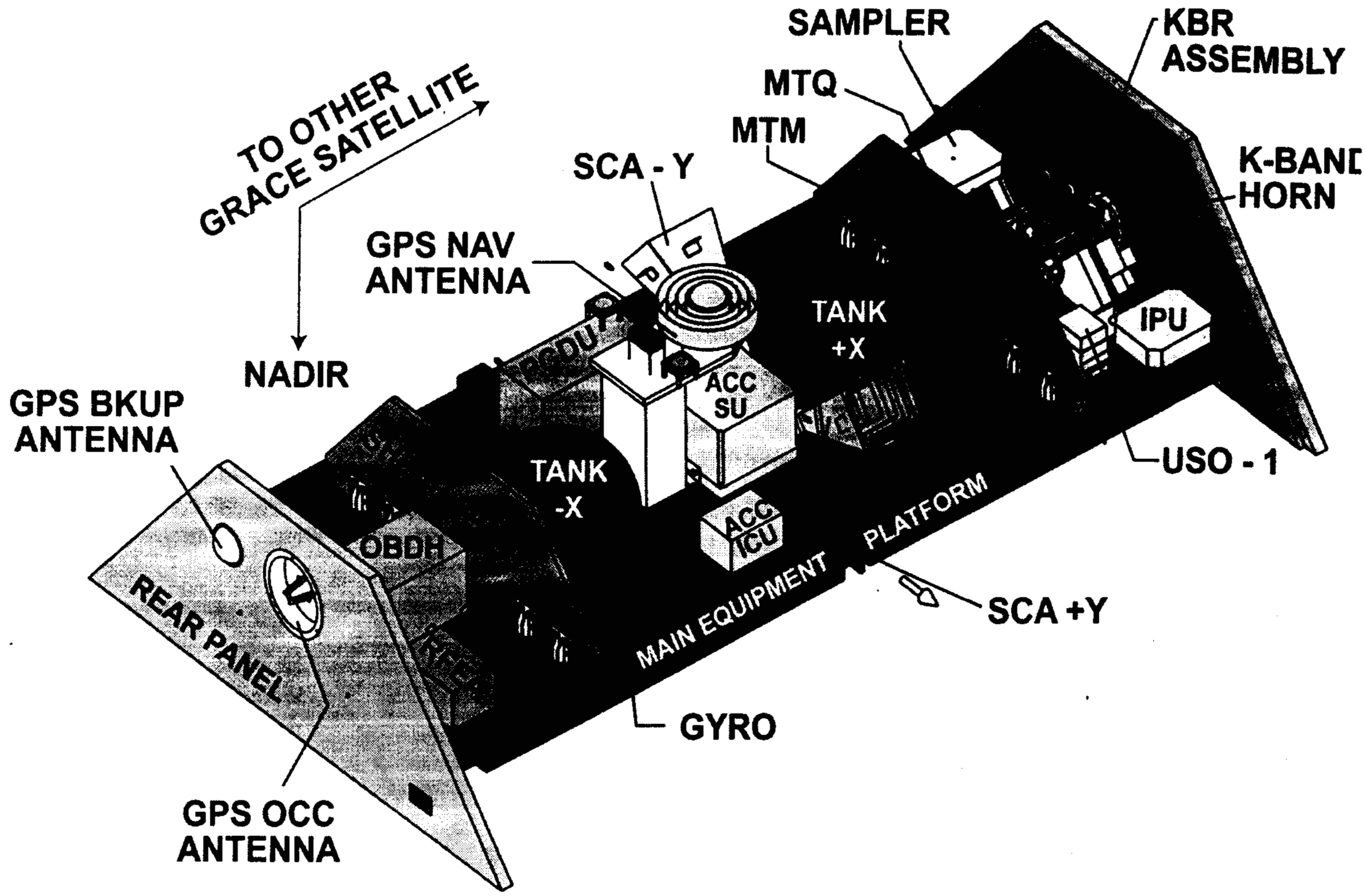

Figure 2. Layout of the components of one of the GRACE satellites. The two GRACE s/c are essentially identical .

In order to connect the microwave phase measurements to motions of the center of mass, the distance between the ranging system phase centers and the center of mass must be stable to better than 3 μm at frequencies of twice per orbit. This is being done by building the satellite structure from low-coefficient-of-thermal-expansion (CTE) composite materials and by careful thermal design. An additional requirement is that the front panel of the spacecraft not move relative to the ranging system antenna, in order to minimize multipath variation.

5- Numerical Accuracy in Analysis

The GRACE biased range measurement has a precision of a few microns. Although this accuracy is about 1 part in 10^{-11} of the 220 km range, when implemented as the difference between two geocentric vectors, it requires a numerical accuracy of better than 1 part in 10^{-12} (1 micron out of 6378 km). Most computers with a 64-bit word provide the IEEE standard of 52 bits for the mantissa (15-16 base 10 digits), although the CRAY SV-1 used primarily for gravity field analysis at UTCSR provides only a 48 bit mantissa (14-15 digits). This representation capability is nearing the limit for GRACE without taking special action, for example, either going to an increased word length (e.g. 128 bit word length) or manually separating integer and fractional parts of the range in the analysis software. On the CRAY, going to the 128 bit word inhibits vectorization, which causes an unacceptable performance reduction. In order to examine the need for software modification as described above, we have performed extensive numerical simulations, compared with results from semianalytic theories (Thomas, 1999), and compared single and multiple CPU simulations. All indications at this time is that current 64 bit machines, with a 48 bit mantissa provide sufficient numerical accuracy that recoding the analysis software to reduce this effect is not required at this time. We intend to further investigate this effect and exchange simulated data for analysis written with the UTCSR and JPL analysis software in the near future.

6- Geophysical Effects

One of the challenging aspects of interpreting the data from GRACE is the removal of high frequency variations in the Earth's gravity field (periods less than 30 days) which will alias into the monthly gravity maps produced by GRACE. Surprisingly, there is significant variability in both the atmosphere and the ocean at few day and even subdaily periods. These high frequency variations must be removed with models in order to reduce aliasing as much as possible. In addition, monthly mean atmospheric pressure variations should be removed from the monthly fields, since if uncorrected, the atmosphere will corrupt the interpretation of regional mass variations as due to other effects, such as local hydrology. For removal of atmospheric effects, we plan to take advantage of the output of numerical weather modelling and forecasting analysis groups around the world, for example at the National Centers for Environmental Prediction (NCEP, United States) and the European Center for Medium Range Weather Forecasting (ECMWF). These groups assimilate a tremendous amount of in situ observations, including barometers, and produce quite accurate pressure maps every 6 hours. Analysis of the quality of these pressure fields by Velicogna and Wahr (1999) indicate that they are generally of sufficient quality to remove pressure effects at the level of less than 1 mbar (or even 0.5 mbar or less for 30 day averages) in most regions. For the ocean, we plan to run a barotropic ocean model, driven by ECMWF winds and pressure. Analysis by Wahr et al. (2000) and Zlotnicki (2000) indicate that such a barotropic model should be good enough everywhere in the world, with the possible exception of near coastlines. Running a full baroclinic model each day, is currently beyond available computation resources.

A potentially troublesome time varying signature is the long term isostatic response of the Earth, from sources such as the melting history of the ice. That is, a combination of more than one current ice thickness change and melting history could fit the geoid change observed by GRACE. However, this problem is soluble and other techniques are able to provide reasonable constraints on the lithospheric signal. Two such techniques are the precise GPS geodetic measurement of lithospheric response and laser altimeter measurements, such as those from the GLAS instrument on ICESAT. A Combined solutions, such as described by [Wu et al, 1999] utilizing all these techniques can significantly reduce the uncertainty introduced by multiple signal sources.

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